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GENERAL MOTORS CORPORATION

TECHNICAL REPORT
ON

NEAR-WAKE IONIZATION BEHIND A SPHERE IN HYPERSONIC FLIGHT
II. INFLUENCE OF FLIGHT CONDITIONS

Sponsored By
ADVANCED RESEARCH PROJECTS AGENCY
Monitored By
U.S. ARMY MISSILE COMMAND

CONTRACT NO. DA-01-021-AMC-11359(Z)
HYPERVELOCITY RANGE RESEARCH PROGRAM
A PART OF PROJECT "DEFENDER"

GM DEFENSE RESEARCH LABORATORIES
SANTA BARBARA, CALIFORNIA

AEROSPACE OPERATIONS DEPARTMENT

TR65-01Q

DECEMBER 1965

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A.Q. ESCHENROEDER c .. TUNG CHEN

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FOREWORD

This report is one of a series of related papers covering various aspects of a broad program to investigate the flow-field variables associated with hypersonic-velocity projectiles in free flight under controlled environmental conditions. The experimental research is being conducted in the Flight Physics Range of GM Defense Research Laboratories, General Motors Corporation, and is supported by the Advanced Research Projects Agency under Contract No. DA-01-021-AMC-11359(Z). It is intended that this series of reports, when completed, will provide a background of knowledge of the phenomena involved in the basic study and thus aid in a better understanding of the data obtained in the investigation.

ABSTRACT

A previous report, Part I under this same title, established a reaction kinetic model for wake ionization. In the present report, the effects of flight speed and ambient pressure on integrated wake electron densities are investigated for nonablating spheres 15mm in diameter. The kinetic model and simplified flow-field description developed in Part I are used to calculate integrated electron densities for velocities between 18 and 22 kft/sec and ambient pressures in the range from 3 to 100 torr. Previously reported experimental results obtained with microwave diagnostics on a free-flight range are used to test the validity of the adopted model. The observed dependences upon velocity and pressure are recovered in the calculations within the combined accuracy of theory and experiment.

CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

A fluid dynamic and chemical kinetic model for describing near wake ionization behind blunt bodies was established in the first report of this series.[1]* A single flight condition typical of many laboratory flight tests at GM Defense Research Laboratories was chosen for this purpose. In the present work, the study is extended one step further in order to test the adequacy of the simplified model over a wide range of flight conditions.

The physical content of the theory will be reviewed only briefly here, since, the computer code,[2] the rationale of the nonequilibrium chemistry[1] and the source of the experimental data[3] are described completely in earlier reports. Inviscid nonequilibrium calculations for the axisymmetric shock layer are used to initiate the solutions around the nose of the body. At angles beyond the termination of the shock layer segment chosen, frozen shock conditions are calculated. Using the conditions along the final ray of the nose-cap shock layer and along the frozen shock locus, a series of streamtube integrations is initiated to continue the solution into the wake. Inviscid convection is assumed for the near wake, precluding the need for transport calculations. An 8-species-by-10 reaction air kinetic model is assumed to describe the composition changes. Only one of the reactions involves charged species.

A separate computer code processes the flow-field outputs to generate the transverse integrals of electron density, which is an experimentally measured quantity directly obtained on the GM DRL free-flight range.[4] Focused transverse microwave probe instrumentation is employed for the measurements.[5] Although radial distributions are obtained both in the measurements and the calculations, their consideration is deferred to a later report.

* Raised numbers in parentheses indicate references, listed at the end of this report.

In the remaining sections of this report the predictions are tested against the observations of wakes behind 15-mm-diameter nonablating spheres at flight speeds between 18 and 22 kft/sec. The velocity dependence most directly reflects the influence of temperature level. Hence, the correct specification of energy barriers along the various reaction paths is subjected to examination. Overall collision order in the reaction scheme is reflected by the pressure dependence at a constant flight speed. Moreover, this variation is indicative of behavior over the flight trajectory of a full-scale vehicle entering the upper portions of the earth's atmosphere.

II. DEPENDENCE OF WAKE IONIZATION ON FLIGHT VELOCITY

Tracing the history of a fluid element through a blunt-body flow field, we see a compression pulse in the shock layer and near-wake. The corresponding temperature levels are influenced by the thermal reco of flow kinetic energy opposed by the drain of energy from translational modes into internal and chemical modes. Because of the combined exponential temperature dependences of the endothermic initial reactions, the incubation of observables is strongly dependent on temperatures (and, therefore, velocity of flight). The sensitivity of the dependence is blunted somewhat by the progress of the reactions, which tend to quench themselves.

In the experiments, sub-scale flight tests in a laboratory range are conducted at constant ambient pressures which may be accurately fixed. In contrast, the velocity of flight is not as easily preset. A common procedure, therefore, has been to obtain a series of measurements at fixed environmental pressures, but at velocities which are systematically varied from flight to flight.

The physical significance of the velocity dependence and the experimental convenience in obtaining it are two reasons for selecting this as an initial test of the physical model evolved in Reference 1. An ambient pressure of 10 torr has been chosen because a major portion of the data was obtained at that condition. Hence, a high level of confidence may be attached to these experimental points.

Figure 1 shows comparisons between measurements and predictions for integrated wake ionization as a function of flight speed. At each axial station plotted (x/d = 3, 10, 20, and 100), the theoretical predictions follow the measured values remarkably well considering the extreme simplifications introduced i the computational model. At 100 sphere-diameters back in the wake, the levels predicted are approximately half those measured. It will be recalled that these measurements are near the sensitivity limit. The predictions are subject to the combined uncertainties of the rate data and mechanisms used a input data.

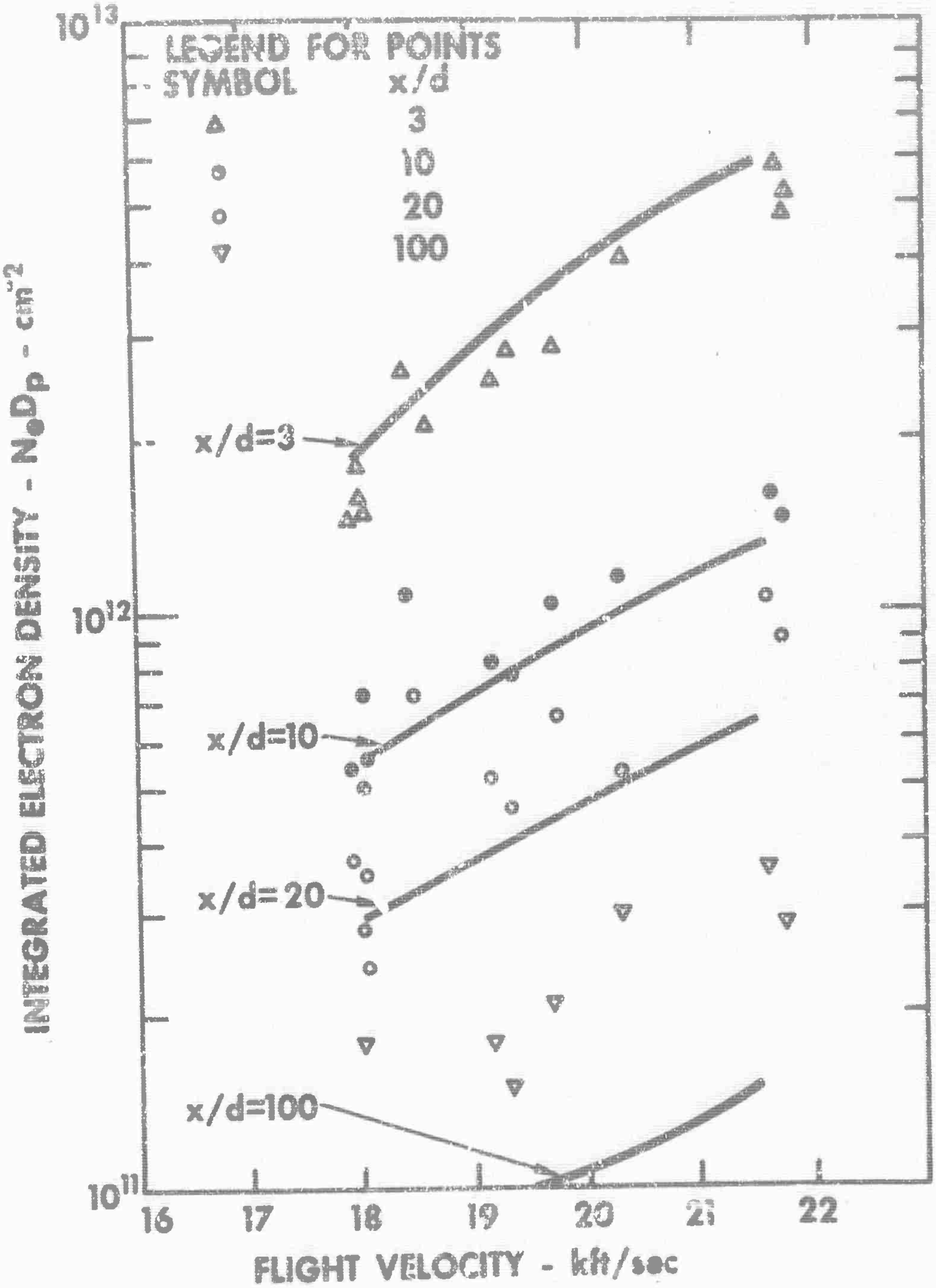

Figure 1 Predictions and Measurements of Velocity Dependence at an Ambient Pressure of 10 Torr

III. DEPENDENCE OF WAKE IONIZATION ON AMBIENT PRESSURE

By cross-plotting the mean curves of experimental data[3] one can obtain the variation of wake ionization with pressure at fixed values of flight speed and axial distance. This set of constraints is representative of the history of an actual reentry trajectory; that is, if we neglect velocity decay we can imagine that such a plot represents the rise of wake ionization during the descent of a vehicle into the atmosphere. In addition to this, the pressure dependence provides a check on the overall reaction order arising in the kinetic assumptions.

Figures 2 through 5 show the variation of integrated electron density with ambient pressure for a flight speed of 21.5 kft/sec. Each figure contains information for some particular station in the wake; conditions at values of 3, 10, 50 and 100 sphere diameters are shown, respectively. Although present experimental practice permits routine flight testing at considerably higher velocity, the above value was chosen on the basis of the large amount of data available in Reference 3. Moreover, the pressure range shown (3 to 100 torr) is broad enough to constitute a rather severe test of the theoretical model. The predictions fall largely within the experimental data until the 50-diameter station is reached (Figure 4). In this region the predictions begin dropping below the scatter band, although the shapes of the curves compare well.

Two possible refinements in the theory would be the addition of attachment and dilution by mixing. Each of these changes would depress the electron density still further at the larger values of x/d. It may be argued also that retention of the lower-bound shock-tube rate coefficient for dissociative recombination would resolve the differences in the region 50 to 100 diameters back. Reference 1, however, shows that this change would put the region from 0 to 50 diameters out of agreement. Such considerations involve factors of two in ionization levels. Because of the extreme simplifications in the wake model and the uncertainties in input rate data, such further alterations are probably not warranted.

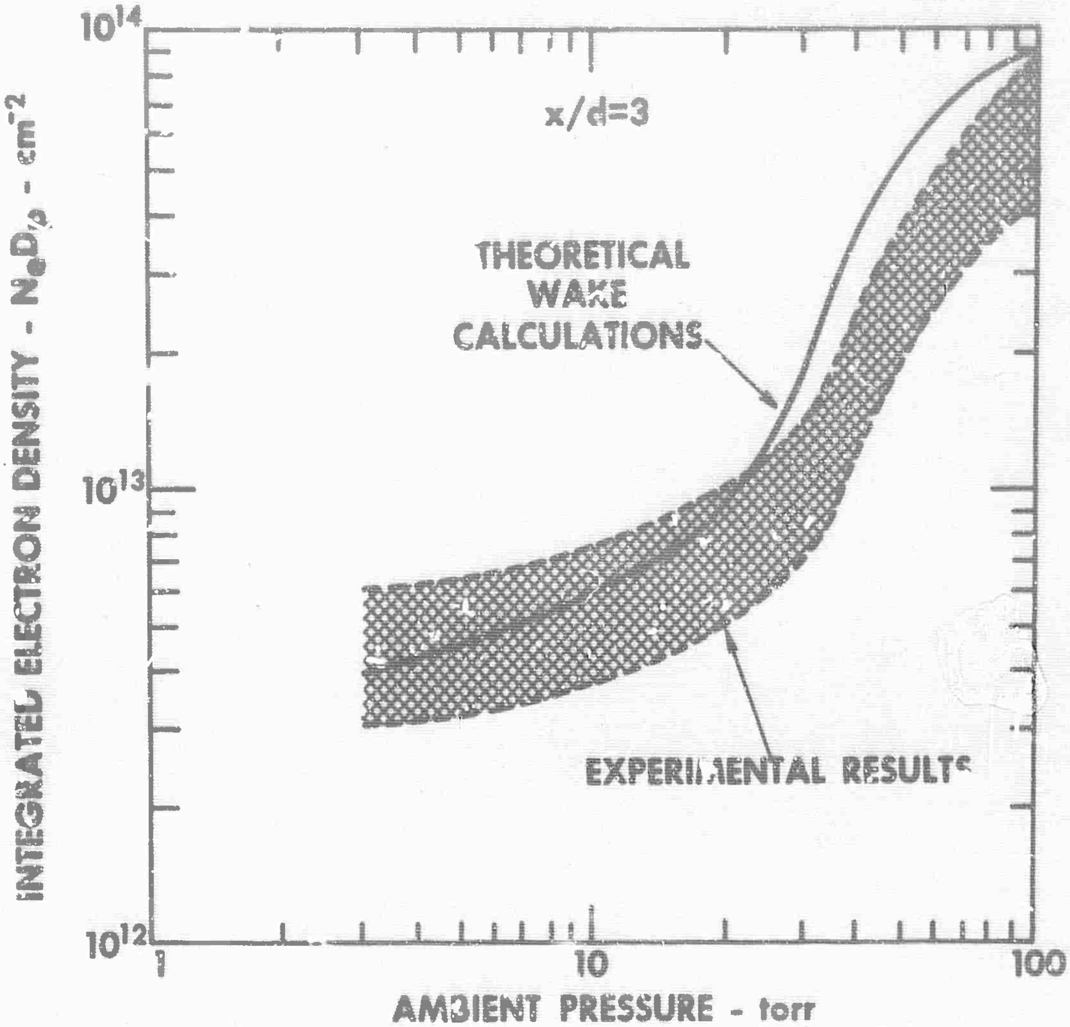

Figure 2 Predictions and Measurements of Pressure Dependence at a Flight Velocity of 21.5 kft/sec, x/d = 3

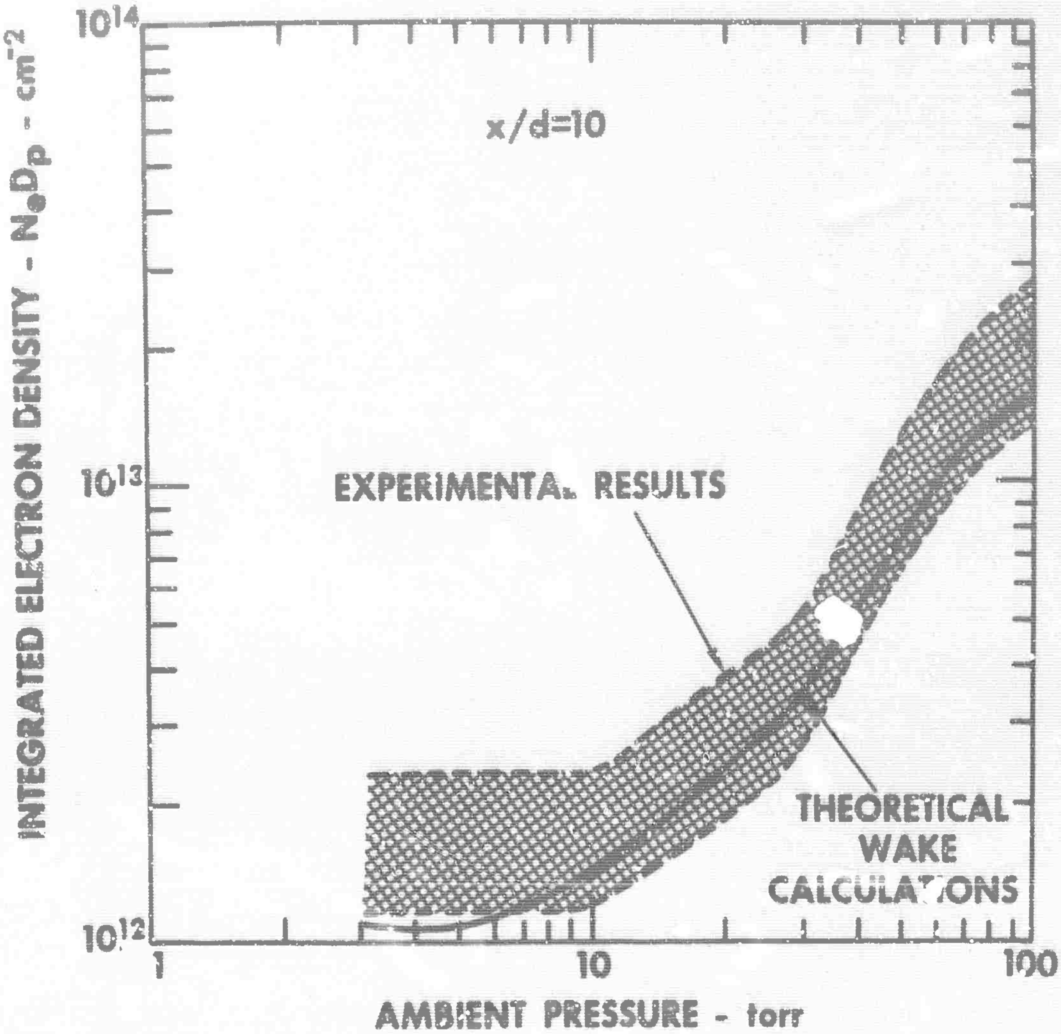

Figure 3 Predictions and Measurements of Pressure Dependence at a Flight Velocity of 21.5 kft/sec, x/d = 10

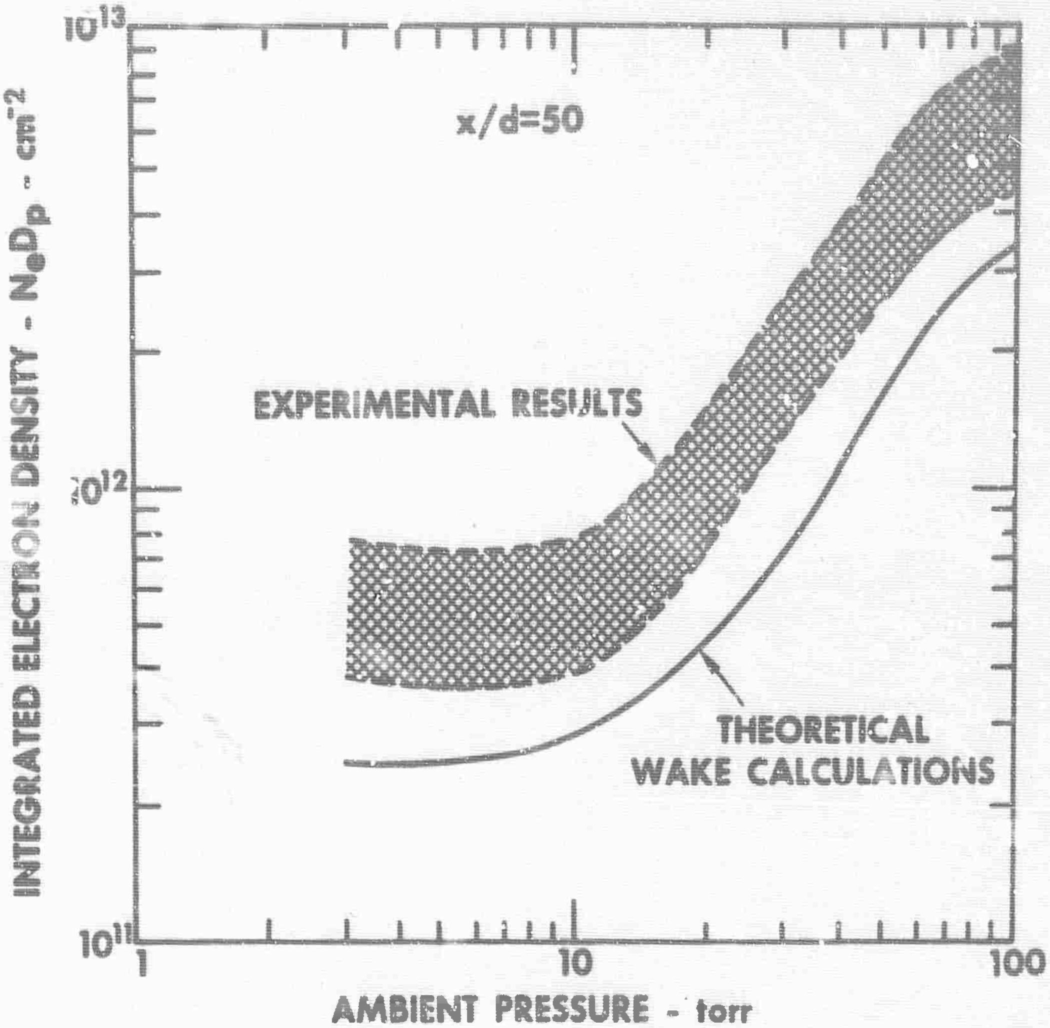

Figure 4 Predictions and Measurements of Pressure Dependence at a Flight Velocity of 31.5 kft/sec, x/d = 50

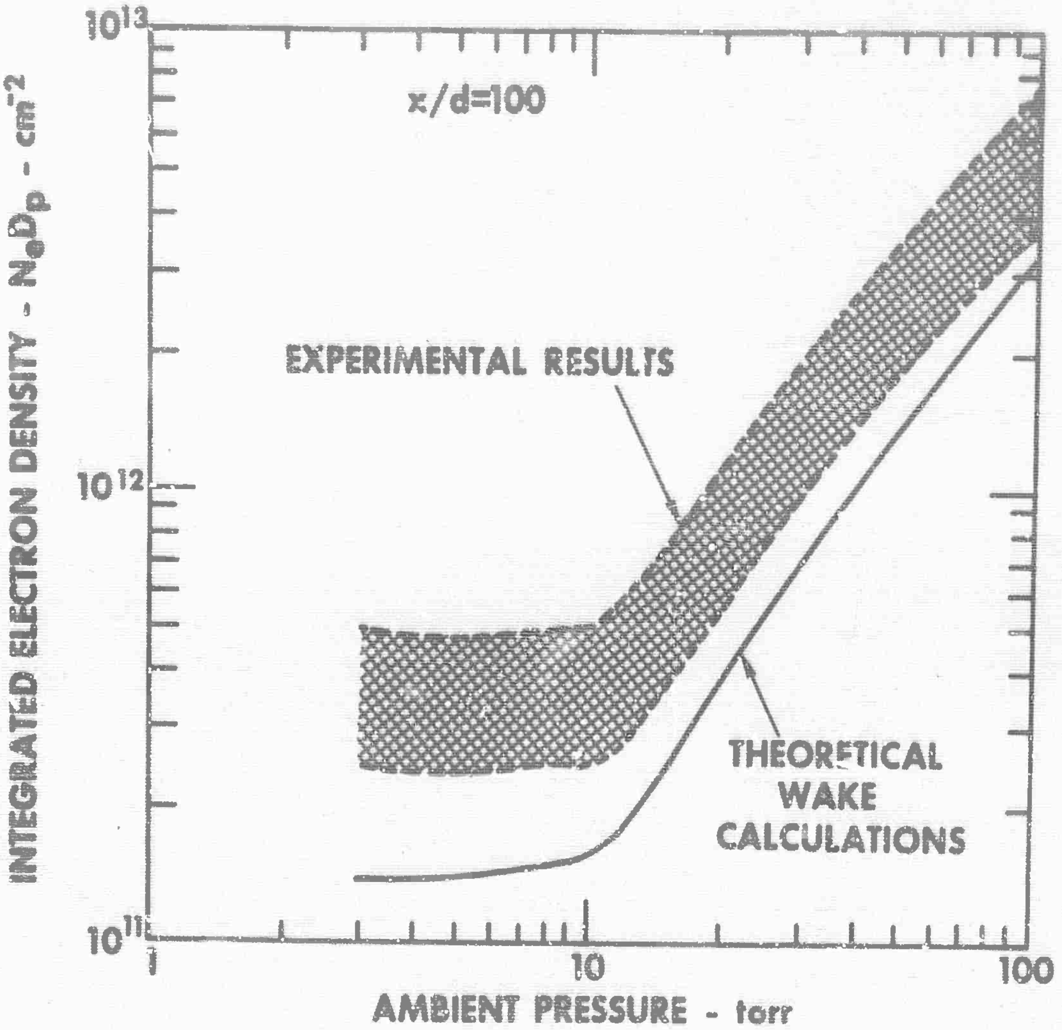

Figure 5 Predictions and Measurements of Pressure Dependence at a Flight Velocity of 21.5 kft/sec, x/d = 100

Regarding the questions of applicability to full scale and the reaction order, a brief digression is helpful at this point. Previously reported experiments[6] on scaling of wake ionization shed light on both questions. Briefly we can summarize the results of Reference 6 by the observation that binary reaction scaling[7] is valid for near-wake ionization over a significant regime of flight conditions. Values of the pressure-diameter product were increased to 750 torr-mm before a factor-of-two deviation appeared between the 5-mm and the 15-mm nonablating-sphere results for a flight speed of 19 kft/sec. First, this indicates that the integrated electron densities observed are predominantly determined by a system of binary reactions; and, second, it assures us that the pressure-dependence curves presented here do indeed relate directly to reentry wake histories because of their scalability. Owing to complex interactions between temperature and pressure in the flow field, the second-order nature of the reaction system cannot be expected to manifest itself as a line having a slope equaling two.

Having examined these general properties of the curves in Figures 2 through 5, we shall now turn to a direct physical interpretation of their shapes. An interesting feature of both theoretical and experimental results is the apparent plateau of ionization level in the neighborhood of 10-torr pressure. Since the electron density integral is the binary scaling analogue of the radiant emission per unit area, it may seem plausible to expect a wake ionization plateau corresponding to the well-known stagnation radiation plateau. Although it is not possible to disprove this hypothesis, the results of the binary scaling experiments do not seem to support it. The termination of the plateau should correspond to the scaling limit if the analogy holds true. In fact, binary scaling is valid[6] for pressures well in excess of 10 torr for 15-mm-diameter spheres.

An alternative explanation may be derived from considerations of the nonequilibrium overshoot following the shock wave. At high pressures, the recombination will follow local equilibrium more closely than at low pressures because of high collision rates. Decreasing pressure decreases density to a point where the reverse reaction can no longer track local equilibrium. The saturation phenomenon

associated with these low collision rates manifests itself as a shock wave overshoot of ionization level frozen into the flow far back into the wake. Further credence in this explanation is lent by the fact that at lower velocities the plateau becomes far less distinct. This is in agreement with the observation that at lower velocities the overshoot becomes far less distinct in a shock-wave reaction zone.

IV. CONCLUDING REMARKS

The dependence of wake ionization on both flight velocity and ambient pressure has been studied for 15-mm-diameter spheres in hypersonic flight. Experimental measurements and theoretical predictions are in harmony for the range of velocities (18 to 22 kft/sec) and pressures (3 to 100 torr) considered in the investigation. Very good agreement is obtained for the first 50 diameters of wake when integrated electron densities are compared. Between 50 and 100 diameters, predictions fall approximately a factor of two below the experimental scatter band. It appears that this overall degree of consistency between observations and computed values supports the physical validity of the assumed theoretical model for a broad range of technically significant conditions.

In particular, the agreement for flight-velocity dependence verifies the assumed temperature factors in the analysis. Activation energies and pre-exponential temperature functions must be correct, in the large, to explain the results presented. Variations in wake ionization with pressure show that the molecularity or collision order of the various kinetic steps must have been specified properly in the calculations. It is intended that these conclusions imply that the principal uncertainties to be resolved lie in the chemical kinetic content rather than in the aerodynamic content of the model.

Thus, the inviscid shock layer solution feeding inviscid convection wake calculations apparently contains enough of the physical aspects to predict successfully the integrated electron densities in near wakes. The 8-species-by-10 reaction kinetic matrix for airflows seems to be sufficiently detailed to provide an adequate chemical description combining the proper heat-bath history with the correct global ionization kinetics. Further tests of the model can be derived from studies of radial ionization profiles and the limits of binary scaling in the wake.

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